DIGITAL TWINS FOR ROAD TUNNELS – EXPECTATIONS MEET REALITY

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ABSTRACT

The German Ministry of transport (BMV) recently published a guideline that defines the basic features of Digital Twins (DT) in the course of the German federal road network and outlines their areas of application. While tunnels already require at least a partially digital environment, which is determined by existing regulations and their implementation, any type of DT must fit into these processes and regulative schemes. In doing so it will automatically redesign and redefine them in order to activate its full potential. That said, safety concerns are raised and need to be addressed. Moreover, the Kritis Regulation of the Federal Office of Information Security (BSI) categorises tunnel control centres as critical infrastructure facilities. Therefore, the number of processes that can be handed over to a DT is already limited due to security implications.

In the DIDYMOS project, the research partners are developing methods and processes for setting up DT for road tunnels, with the aim to implement them as a part of optimized operating approaches. In this context, the authors conducted extensive interviews with all stakeholder groups involved in tunnel operation. The results of the interviews show that, on the one hand, there is great curiosity about such approaches, but on the other hand, substantial concerns have been expressed as to whether tunnel operation needs to be redefined and reorganized if a DT is to be introduced into everyday operations. The interviews also address which tunnel operation tasks can or may be automated by DTs.

In this article, the authors present a summary of the interview results and highlight where stakeholder expectations and technical implementation concepts correlate or conflict with each other. Furthermore, preliminary dashboards of the developmental DT and how analyses can be carried out for the daily work are presented.

Keywords: Digital twin, road tunnel, tunnel operation, predictive maintenance, AI

1. INTRODUCTION

Digitalization has become an essential component of the construction industry, encompassing all phases of project development, including the initial planning phase, the construction phase, and the subsequent maintenance and operational phases. The German 'Masterplan BIM' guideline is primarily centered on the planning and construction phase [1]. In the meanwhile, there are no standards and guidelines on the implementation of digitalization and BIM in the operational phase. This can be primarily ascribed to the heterogeneity of the structures. Due to the necessity for a high level of technology in tunnels to ensure user safety, a large number of digitized operating points already exist in these structures, while bridges and troughs still have comparatively less complex operating scenarios. This means that there is need of different approaches in the implementation of digital twins (DTs) as measure for maintenance and operation of the structures.

This issue is being addressed in the DIDYMOS project, which is funded by the BMV as part of the mFund funding initiative. For the first time, research is being conducted into the requirements and conditions for implementing DT-s for road tunnels. In the project methods for structural acquisition and digitization, as well as maintenance planning and operational optimization will be developed [2].

The following section primarily focuses on the framework conditions for the development of DTs, and presents the results of the expert interviews and discusses them in this context. However, the development of digital as-is models is only briefly described, with reference being made to parallel publications by the authors.

2. DIGITAL TWINS

2.1. Terms and conditions for developing DTs and DIDYMOS

Building Information Modeling (BIM) represents a collaborative methodology that enables the coordinated exchange and management of digital building information throughout the entire life cycle of a structure. At the core of BIM are digital building models that integrate geometric and semantic data.

However, these digital models, often referred to as BIM models, do not fully correspond to the definition of a DT [3]. Rather, DTs are an extension of such models, incorporating a continuous data link between the physical structure and its digital representation. This encompasses, in particular, the integration of real-time data, condition monitoring functions, and analysis and decision support systems that facilitate bidirectional data exchange between digital and physical objects [4]. A DT is thus composed of three primary components: a digital model, a physical equivalent, and the exchange of data between these two components. This data exchange can take place in several directions, i.e. from the digital model to its physical equivalent, vice versa, or in both directions in parallel [5].

A digital model of the structure is therefore a fundamental prerequisite for building a DT. If such a model is available, the model must be analyzed according to its lifecycle phase and assessed regarding its quality and level of detail. In particular, the model must be examined for its suitability as a foundation for DT. While verifying the existence of a model is usually straightforward, assessing its accuracy and completeness is considerably more complex.

In the case of existing tunnel structures, however, such models are often missing or outdated [6]. Consequently, reconstructing or updating digital representations of these assets from available tunnel documentation, such as drawings, reports, or point clouds, is a necessary first step. When performed manually, this process is highly time-consuming and laborious.

The DIDYMOS project addresses this challenge by developing methodologies for the (semi)automated generation of digital tunnel models using Artificial Intelligence (AI)-based techniques [7]. Different approaches are conceptualized based on the available data of the structures [8]. In addition, all partners are engaged in research related to the development of specific DTs and the implementation of specific use cases, utilizing AI-based analysis routines. Based on this foundation, some critical research questions arose:

- How can DT be integrated into tunnel operations given existing safety, regulatory, and stakeholder constraints?
- What technical and processual obstacles have to be tackled while implementing DT in tunnel operations?

For answering those questions and subsequently describing the accompanying use cases, it was imperative to undertake expert interviews. In doing so, it was possible to identify the needs and requirements for digital support in operation and maintenance, as well as to capture concerns regarding implementation and application.

2.2. Boundary condition for the development of DTs

The initial phase in developing a comprehensive concept for DTs was initiated by the BMV, which established a framework for the development of DTs [9]. This development must be in accordance with the normative regulations. The construction must comply with the requirements of ZTV-ING Part 7 [10], in conjunction with the parallel requirements of DIN 1076 [11] and RI-EBW-PRÜF [12]. This provides the framework for inspection and maintenance, including the evaluation of the structural integrity of the tunnel structure.

In accordance with the stipulations set out in the European Directive [13], a set of administrative and structural requirements were established within Germany for the operation of tunnels, with the objective of ensuring the safety level of such infrastructure. These were initially documented in RABT 2006 [14] and have since been transferred to RE-ING [15].

In addition, tunnel control centers are considered to be part of the federal critical infrastructure. This necessitates restrictions on the free availability of security-related data.

Furthermore, local conditions or individual operational philosophies may create framework conditions that can vary from one structure to another and must also be taken into account.

3. EXPERT INTERVIEWS

3.1. Interview results

As part of the expert interviews, a total of 14 experts (stakeholders) from various areas of tunnel operations were interviewed, including administrative authorities, tunnel managers, safety officers, and tunnel monitoring personnel. The aim was to identify which processes could be supported by an AI-based DT in tunnel operations. The interviews addressed the following thematic blocks:

1. General information
2. Processes and data
3. Forecasting
4. Data exchange / Visualization
5. Target Areas and Use Cases
6. Operational condition assessment and evaluation of tunnel ventilation system
7. Structural condition assessment and evaluation of tunnel linings
8. AI

Thematic blocks 1 and 2 provided an overview of relevant processes and data, as well as the experts' assessments regarding the use of the DT. In block 3, the experts explained the operational context in which they could imagine accessing forecasts in the course of decision-making. Block 4 focused on formulating requirements for the DT interface and visualization requirements. In block 5, specific use cases and target areas were described, which, from the experts' perspective, should be addressed by the DT. Blocks 6 and 7 focused on the selection and evaluation of Key Performance Indicators (KPIs) for both use cases mentioned above "Tunnel Ventilation" and "Tunnel Linings," which are examined in detail within the DIDYMOS project. Finally, Block 8 included discussions on experiences and requirements related to the use of AI in tunnel operations and maintenance. Excerpts from the results of this user requirements analysis are presented below. When recording user-specific requirements, the tunnel experts explained what additional information they would consider helpful when using DT. These are summarized in Table 1.

Table 1: Overview of expert/Stakeholder requirements for information displayed by a DT

Stakeholder requirements
Overview of structural and technical condition
Plant status and fault tracking
Cost development
Monitoring of structural damage
Statement on the completeness of data and documents
Statement on regulatory compliance information
Maintenance scheduling
Operational strategy
Traffic data
Condition of all tunnels at a glance

According to the experts, the DT of a tunnel should provide a comprehensive and up-to-date overview of the condition of the structure and its technical systems. Malfunctions and damages must be recorded, visualized, and tracked throughout the entire lifecycle of the structure. Cost development should also be represented transparently. Furthermore, experts emphasized the importance of a complete overview of all relevant data and documents via the DT. This refers to a centralized storage of all relevant information/data for the entire structure (single source of truth).

The DT should also provide information on the regulatory compliance of the structure and indicate when the next maintenance of specific equipment components is due. Information on operational strategies should be integrated, as well as traffic-related data that are crucial for improving traffic management and optimizing tunnel availability. Finally, the various DTs should be interconnected to enable a clear overview of the condition of all tunnels within the area of responsibility — ideally at a glance.

Additionally, the use of AI in tunnel operations and maintenance was discussed. Stakeholders outlined the potential and added value of AI from their perspective. These are presented in Table 2.

Table 2: Expert/Stakeholder perspectives on the Added Value of AI in tunnel operation and Maintenance

AI potentials and added value in tunnel operation and maintenance
Automated analysis of real-time and measurement data
Processing big data
Fast retrieval of desired information (Document Analysis)
Experience-based automated assessment (Lessons Learned)
Automated image and video analysis
Relief of personnel from specific tasks
Automated detection of anomalies and patterns through continuous monitoring
Automated generation of asset models
Enhancing damage identification processes
Automated suggestion generation for planning and renovation
Automated detection of incidents and traffic congestion

In summary, DTs offer numerous advantages for technical and organizational processes, according to the experts**.** A key benefit should be the high data quality enabled by continuous synchronization with the physical object, which makes precise analyses and supports decision-making possible. DTs can improve collaboration and reduce misunderstanding by visualizing and exchanging complex information. Another major advantage is the support of predictive maintenance: by analyzing real-time and historical data, potential failures can be identified early or prevented as far as possible, which increases operational safety and reduces costs.

3.2. Dashboard according to expert interview results

Following the results of the stakeholders' requirements of the DT, the project partners have developed concepts for several dashboards. These dashboards are still in the design phase. The provisional dashboards facilitate the visualization of the front-end layer of the digital twin, thereby displaying all the essential information regarding tunnel operation. As illustrated in Figure 1, the provisional dashboard represents one of the use cases that has been defined within the DIDYMOS project. The use case demonstrated is that of the structural condition assessment and evaluation of the tunnel’s inner lining.

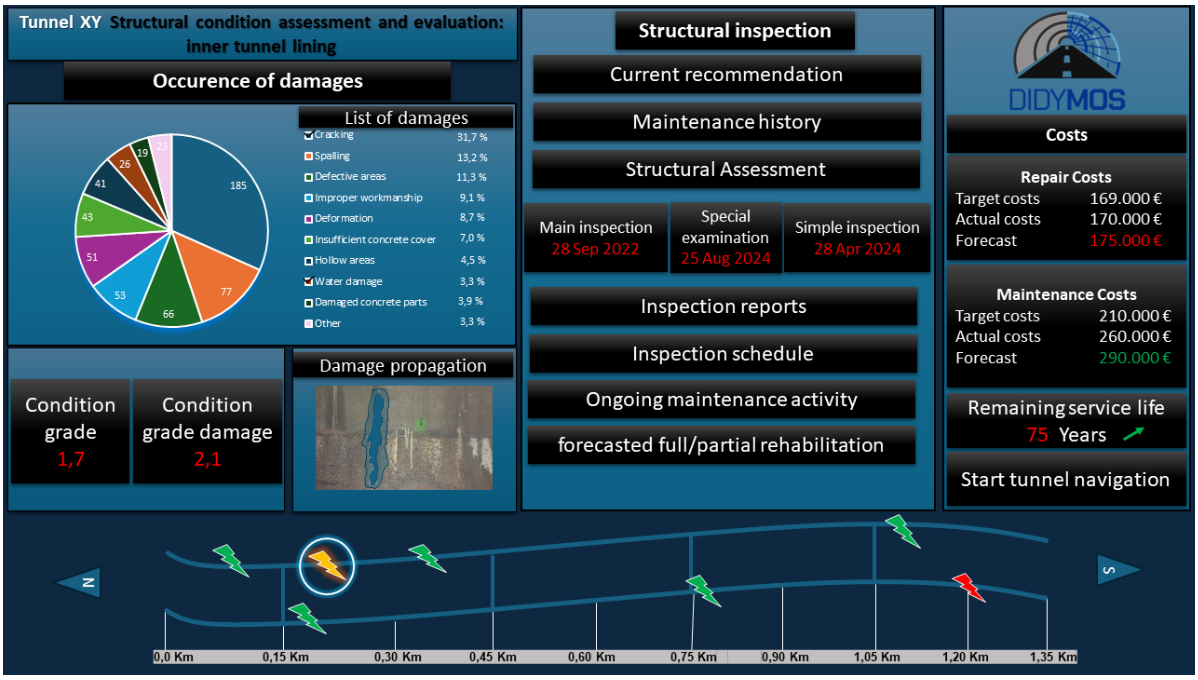

Figure 1: Provisional dashboard for the use case "structural condition assessment and evaluation of the tunnel inner lining" (Source: RUB TLB)

The provisional dashboard has been designed to incorporate as many of the requirements of the stakeholders as possible. The structural condition of the tunnel, the maintenance schedule and the inspection history are all displayed in a compact format and are easily locatable. The subsequent components are presented in order to illustrate the propagation of each documented damage, as well as the condition grade assigned to each individual damage. In addition, the requirement for cost development, encompassing its various cost categories, is presented. Moreover, the current vision entails the facilitation of navigation through a 3D model of the tunnel structure in its existing state. The navigation of the tunnel, including the location of all damage and the technical equipment information, can subsequently be located on an additional dashboard.

4. CHALLENGES IN THE IMPLEMENTATION OF DIGITAL TWINS

From the experts' perspective, despite the numerous advantages of a DT, there are several significant aspects that must be considered during development**.** For instance, the implementation and operation of a DT not only require specialized hardware and software, but also qualified personnel capable of deploying and maintaining. Moreover, there is a risk of excessive reliance on technology when decisions are made solely based on digital models. If the real-world situation is not sufficiently taken into account, this can lead to misjudgments. Therefore, the significance of high-quality data is paramount to the efficacy of a digital twin.

A further critical issue is the persuasion of those who are resistant to the adoption of digital technologies. According to stakeholders, many organizations have employees who are skeptical about new technologies or reject them outright. A meticulous and methodical change management process is imperative in fostering acceptance within this context. The potential dangers of generalization should not be underestimated either. It is important to note that a digital twin based on general assumptions and not adapted to the specific requirements of a structure may not be able to adequately reflect these special features. This may result in inaccurate assessments, especially when the decision-making or decision support for controlled processes is AI-based. As the volume of collected and analyzed data increases, so does the risk of information overload. Without effective filtering and visualization methods to identify KPIs relevant to the specific application, it can become challenging to extract meaningful insights and make effective decisions.

A further key finding from the expert interviews conducted is that there is currently no uniform understanding of what a digital twin must achieve in the context of tunnel operation and what its specific design should look like. Having 16 federal states in Germany, each with a unique organizational structure, leads to a large heterogeneity. The challenges associated with developing a nationwide standard for DTs of tunnel structures is compounded by the heterogeneity of the software landscape and the varied responsibilities and administrative structures across different federal states. As is the case of BIM, this results in isolated solutions that are interoperable to a limited extend, thereby constraining the advantages to individual structures. Consequently, conducting a comprehensive network analysis, particularly in the context of forecasting life cycle costs and strategic maintenance planning, is impracticable under these conditions, despite this representing the optimal goal of development.

In addition to clarifying the terminology, it is imperative that there are clear administrative, legislative and technological framework conditions in place to enable standardized implementation. From an administrative perspective, there is a necessity for the coordination of responsibilities and the establishment of binding guidelines at both the federal and state levels. The objective of this coordination is to standardize data modelling, access rights and update cycles. In the context of legislation, the Federal Highways Act and associated administrative regulations would require amendments. Such adjustments are deemed necessary in order to incorporate the DT into operational processes.

5. SUMMARY AND CONCLUSIONS

DTs have a lot of potential to enhance the technical and economic efficiency of road tunnel structures, thereby increasing operational availability and ensuring user safety. However, it is imperative that standards are defined and established with utmost urgency to ensure the interoperability of conceptual approaches and to establish a uniform framework for the structures. Moreover, the development of isolated solutions from a network perspective is to be avoided. These principles are applicable not only in the context of tunnel structures but also in the context of other structures. The DT's working method offers a substantial added value that derives from the comprehensive, uniform digital data management at network level, and not primarily from the modeling of individual structures and the linking of existing information with a 3D model of the structure. Evidently, from a network standpoint, there is also rationale for integrating DT data concerning tunnel structures with those pertaining to bridge structures, retaining walls, and ancillary transport and drainage facilities. It is only on this basis that reliable and comparable statements can be made about the life cycle costs of the federal transportation network with overarching maintenance strategies and investment requirements. A DT, when used in conjunction with a dashboard for the front-end results, has the potential to engender substantial enhancements in the efficiency and operation of tunnel structures.

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